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Influence of mineral fertilization on mechanical properties of the chosen elements of bean pod inner structure

Piotr Kuźniar

University of Rzeszów, Department of the Farm and Food Production Engineering,
Zelwerowicza 4 str, 35-601 Rzeszów, Poland, pkuzniar@univ.rzeszow.pl

Summary. The study presents characteristics of strength properties of the selected structure elements of bean pods of varieties: Narew, Nida, Warta and Wawelska with alternating fertilization with nitrogen and phosphorus. The abdominal seam bundles of bean pods were characterized with lower crippling stress, deformation and conventional modulus of elasticity than the vascular bundles of dorsal seam. At fertilization with phosphorous, abdominal and dorsal seam bundles of the pods of the analyzed bean varieties were characterized with larger deformation and lower strength to breaking and modulus of elasticity than when fertilized with nitrogen. The used macroelements had the largest influence on crippling stress and the smallest one on modulus of elasticity of fibre layer in a pod. The applied phosphorous doses exerted larger influence on the increase of stress and deformation than the nitrogen doses, and the modulus slightly increased with nitrogen fertilization.

Key words: bean pod, structure elements, crippling stress, deformation, modulus of elasticity.

INTRODUCTION

One of the unfavourable features of leguminous plants is a tendency to crack their pods and flake their seeds before and after harvesting [5, 13, 14, 17, 18].

Vulnerability of pods to cracking is a variety feature and is determined by their anatomic and morphologic structure. The main feature which facilitates cracking of a pod is the structure of its endocarp in which there is a fibre layer consisting of severely thickened sclerenchymatic cells situated diagonally to fruit's axis. Due to various arrangement of microfibers in cell walls during drying they shrink in various directions and the pod cracks along abdominal and dorsal seams. Fibre content and structure in vascular bundles and walls of the shell is the most significant among the elements of pod internal structure [2, 4, 10, 11, 16, 17, 20].

The aim of the study was to determine the influence of mineral fertilization on strength properties of the chosen structure elements of bean pods.

MATERIAL AND METHODS

The research was carried out in 2008-2010. Bean was cultivated in the experimental field of the Department of the Farm and Food Production Engineering in Rzeszów. Four nitrogen doses (0, 30, 60 and 90 kg·ha^{-1}) and phosphorus doses (0, 40, 80 and 120 kg·ha^{-1}) were applied before sowing. The research was conducted on pods of bean cultivated on dry seeds of the varieties: Narew, Nida, Warta and Wawelska, which were characterized by varied seed and pod size (Tab. 1).

Table 1. Pod characteristics (average values) of the tested bean varieties

Specification	Narew	Nida	Warta	Wawelska
Nitrogen fertilization				
Dimension of pods[mm]:				
Length	93,3	92,6	108,0	115,3
Width	10,0	10,0	9,6	10,8
Thickness	9,7	9,0	8,8	9,3
Number of seeds in a pod	4,8	4,2	4,5	3,9
Phosphorus fertilization				
Dimension of pods [mm]:				
Length	93,0	89,5	103,7	112,3
Width	10,1	10,4	10,0	11,2
Thickness	9,3	9,1	8,9	9,8
Number of seeds in a pod	4,6	4,0	4,3	3,7

Pod dimensions were calculated using an electronic slide calliper with the accuracy of 0.01 mm. Length was measured from the beginning of stalk to the peak, and width and thickness in cutting plane of perpendicular to main axis of the fruit, leading through its centre. Thickness and width of a fibre layer and seam bundles were measured using an electronic dial gauge with the accuracy of 0.001 mm. Surface of cross section of the analyzed pod structure elements was calculated as a product of width and thickness.

Strength research covers such pod structure elements as:
– fibre layer,
– seam sclerenchyma bundles; abdominal and dorsal.

The research was conducted with the use of testing machine ZWICK with which, for the above mentioned pod structure, the following elements were determined: critical stress, modulus of elasticity (Young's modulus) and deformation [3, 6 - 9, 15, 19]. In order to separate fibre layer and seam sclerenchyma bundles from the other tissues, bundles were placed for 15 minutes in boiling water. Parenchyma tissues macerated in this way were removed (scraped off) with a blunt side of a scalpel so as not to damage sclerenchyma [12, 15]. For the purpose of resistance tests ca 2 mm straps were cut from a fibre layer parallel to the direction of fibre location.

Measurements were conducted on 20 pods for each of the tested varieties with their humidity within the range of 12.4-13.8%.

The result was statistically analyzed with Statistica 9 program with which variance analysis and LSD significance test were carried out [1].

RESULTS

The seams of Warta variety (Tab. 2) characterized with the vitally smallest width, thickness and cross section area of vascular bundles of abdominal and dorsal seam. The widest pod structure elements were observed in the Narew variety, and the thickest and with the largest cross section area were found in the Wawelska variety.

Except for the thickness in both the used types of fertilization and cross section area, abdominal seam bundles were characterized with significantly larger dimensions with nitrogen fertilization.

While analyzing data in Table 2, it also should be emphasized that pods of all the tested bean varieties displayed larger features in question for abdominal and dorsal bundles after application of phosphorous fertilization in comparison with nitrogen fertilization.

The influence of applied nitrogen doses (Tab. 3) on the analyzed geometric features of seam bundles of bean pods of the tested varieties was very diverse. Statistically significant changes were discovered only for the thickness of abdominal seam bundles of Nida pods and all the analyzed features of abdominal seam bundles of Warta pods. A similar relation can be observed by comparing mean values of these qualities from all the tested varieties. Discussed features of abdominal and dorsal seam bundles have the minimum value with no nitrogen dosage. The maximum values are reached with 30 and 60 kg nitrogen per hectare, and with the highest dose they decrease, yet they still are higher than at the first nitrogen dose.

The influence of applied phosphorous doses (Tab. 4) on the analyzed geometric features of abdominal and dorsal seam bundles of bean pods of the tested varieties was, similarly to nitrogen fertilization, highly diverse. Statistically significant changes were found only for the thickness of abdominal (increase) and dorsal (decrease)

Table 2. Mean values of dimensions and cross section area of abdominal (A) and dorsal (D) seam bundles of pods of the tested bean varieties

Specification	Seam bundles	Narew	Nida	Warta	Wawelska	Average
Nitrogen fertilization						
Width [μm]	A	674 bc	583 ab	511a	669 bc	609,3 II
	D	608 b	564 b	489 a	564b	556,1 I
Thickness [μm]	A	156 a	180 b	149 a	196 b	170,2 I
	D	158 ab	176 b	152 a	200 c	171,5 I
Surface of cross section [mm^2]	A	0,108 b	0,106 b	0,077 a	0,132 c	0,106 I
	D	0,097 b	0,101 b	0,076 a	0,114 b	0,097 I
Phosphorus fertilization						
Width [μm]	A	739 b	673 a	633 a	637 a	670,4 II
	D	626 a	606 a	574 a	612 a	604,3 I
Thickness [μm]	A	200 b	199 b	166 a	192 b	189,5 I
	D	187 a	186 a	168 a	209 b	187,7 I
Surface of cross section [mm^2]	A	0,151 c	0,133 bc	0,108 a	0,125 ab	0,129 II
	D	0,118 bc	0,114 ab	0,0980a	0,131 c	0,115 I

*different letters in row and Roman numerals in column signify significant differences for the significance level α = 0.05)

Table 3. Values of dimensions and cross section area of abdominal (A) and dorsal (D) seam bundles of pods of tested bean varieties for applied doses of nitrogen

Specification	Dose [kg·ha^{-1}]	Narew	Nida	Warta	Wawelska	Average
Abdominal seam bundle						
Width [µm]	0 30 60 90	668 721 675 633	557 576 565 635	513 526 497 507	615 646 723 692	588,3 617,3 615,0 616,8
Thickness [µm]	0 30 60 90	127 a 173 b 155ab 170 b	162 189 176 193	148 147 168 134	209 202 195 177	161,7 177,7 173,1 168,8
Surface of cross section [mm^2]	0 30 60 90	0,086 0,128 0,108 0,108	0,091 0,110 0,101 0,123	0,077 0,079 0,082 0,068	0,131 0,132 0,142 0,123	0,096 0,112 0,108 0,106
Dorsal seam bundle						
Width [µm]	0 30 60 90	600 615 614 602	578 551 564 563	418 a 523 b 548 b 468 a	548 540 576 590	536,0 557,2 575,5 555,8
Thickness [µm]	0 30 60 90	157 168 151 155	157 168 197 182	116 a 166 b 162 b 164 b	208 206 195 190	159,6 176,9 176,5 172,9
Surface of cross section [mm^2]	0 30 60 90	0,096 0,106 0,095 0,094	0,090 0,093 0,114 0,105	0,050 a 0,089 b 0,088 b 0,077 ab	0,118 0,114 0,112 0,111	0,088 0,100 0,102 0,097

*different letters in column signify significant differences for the significance level α = 0.05

Table 4. Values of dimensions and cross section area of abdominal (A) and dorsal (D) seam bundles of pods of the tested bean varieties for applied doses of phosphorous

Specification	Dose [kg·ha^{-1}]	Narew	Nida	Warta	Wawelska	Average
Abdominal seam bundle						
Width [µm]	0 40 80 120	784 722 689 760	669 651 710 663	693 606 567 666	567 a 668 ab 611 ab 701 b	678,5 661,8 644,3 697,5
Thickness [µm]	0 40 80 120	179a 202 ab 192 ab 229 b	176 201 206 212	182 140 182 161	194 168 202 206	182,6 177,6 195,8 202,1
Surface of cross section [mm^2]	0 40 80 120	0,143 0,150 0,136 0,176	0,118 0,132 0,145 0,138	0,130 0,083 0,103 0,114	0,113 0,114 0,125 0,146	0,126 0,120 0,127 0,144
Dorsal seam bundle						
Width [µm]	0 40 80 120	589 628 649 637	603 644 582 594	622 b 519 ab 514 a 642 b	572 624 610 640	596,5 603,8 588,7 628,2
Thickness [µm]	0 40 80 120	187,9 ab 219,5 b 166,9 a 175,3 a	200,8 194,7 175,4 173,8	177,6 159,2 180,0 154,9	201,3 193,0 228,3 214,4	191,9 191,6 187,7 179,6
Surface of cross section [mm^2]	0 40 80 120	0,112 0,139 0,110 0,114	0,121 0,126 0,103 0,105	0,112 0,086 0,094 0,100	0,116 0,121 0,143 0,141	0,115 0,118 0,112 0,115

*different letters in column signify significant differences for the significance level α = 0.05

Table 5. Strength properties of fibre layer of abdominal (A) and dorsal (D) seam bundles of the pods of tested bean varieties

Specification	Seam bundles	Narew	Nida	Warta	Wawelska	Average
Nitrogen fertilization						
Critical stress [MPa]	A	99,6 bc	61,8 a	117,7 c	80,6 ab	89,9 I
	D	126,3	124,5	111,6	129,9	123,1 II
Deformation [%]	A	4,4	4,3	6,2	4,5	4,8 I
	D	7,1	7,7	7,7	6,4	7,2 II
Modulus of elasticity [MPa]	A	2528,8 c	1662,8 a	2060,9 ab	2184,7 bc	2109,3 I
	D	1937,3 ab	1856,7 ab	1595,9 a	2265,4 b	1913,8 I
Phosphorus fertilization						
Critical stress [MPa]	A	70,3 a	56,3 a	93,4 b	99,5 b	79,9 I
	D	101,5	117,5	113,4	121,5	113,5 II
Deformation [%]	A	6,6	5,7	7,2	6,2	6,4 I
	D	5,8	8,2	7,8	8,6	7,6 II
Modulus of elasticity [MPa]	A	1222,8 a	1408,4 ab	1369,6 ab	1774,8 b	1443,9 I
	D	2016,7 b	1567,6 a	1605,9 ab	1463,6 a	1663,5 II

*different letters in row and Roman numerals in column signify significant differences for the significance level α = 0.05)

seam bundle and width of dorsal seam bundles of the Warta pods (increase) and width of abdominal seam bundles of the Wawelska variety pods (increase).

A relation between nearly all the tested varieties can be observed when comparing mean values of the analyzed qualities of abdominal seam bundles of bean pods. At first the relevant features of abdominal seam bundles decrease after the application of the second and the third phosphorous dose, and then they increase to values higher than at zero dose. The width of seam bundles of Narew, Nida pods and all the three features of this bundle in Warta pods constitute an exception. As regards dorsal seam bundles in comparison to abdominal seam, decreasing tendency occurs more frequently, especially for the width of this pod element.

Abdominal seam bundles of the Nida pods displayed the smallest stress, deformation and modulus of elasticity (tab. 5). In case of dorsal seam bundles the smallest stress and deformation was observed for the Narew variety pods, and the smallest modulus for the Warta pods. The abdominal seam bundles of the Warta pods were the most resistant to tearing and underwent the largest lengthening, while the largest modulus was present in the bundles of Narew (with nitrogen fertilization) and Wawelska (with phosphorous fertilization). The Wawelska variety pods displayed the largest crippling stress of dorsal seam bundle, Nida and Warta (with nitrogen fertilization) as well as Wawelska (with phosphorous fertilization) displayed the largest deformation, while the largest modulus was observed in the Narew variety.

Dorsal seam bundles (Tab. 5) demonstrated a significantly higher crippling stress, deformation and conventional modulus of elasticity than abdominal seam bundles. The exception constituted Narew variety in which abdominal seam bundles were characterized with a slightly higher value of modulus of elasticity (with nitrogen fertilization) and larger deformation (with phosphorous fertilization), as well as the Wawelska whose abdominal seam bundles displayed a higher modulus of elasticity with phosphorous fertilization. With phosphorous fertilization sclerenchyma bundles of seam bundles of the tested bean varieties manifested a lower resistance to tearing and modulus of elasticity, and larger deformation than with nitrogen fertilization. The exception was the Narew variety in which with phosphorous fertilization dorsal seam bundle underwent smaller lengthening and it was characterized with a slightly higher modulus of elasticity.

Table 6. Average values of thickness [µm] of the fibre layer of pods of the tested bean varieties

Fertilization	Narew	Nida	Warta	Wawelska	Average
Nitrogen	77,6 a	67,2 a	72,3 a	95,5 b	78,16
Phosphorous	92,3 b	68,2 a	70,3 a	102,8 c	83,39
Average	84,9 b	67,7 a	71,3 a	99,1 c	80,75

*different letters in row signify significant differences for the significance level α = 0.05

The largest mean fibre thickness (99,1µm) was observed in the Wawelska variety pods (Tab. 6), whereas the Nida pods were characterized with the thinnest fibre layer. The same diversity between varieties as regards thickness of the tested element of pod structure occurred with nitrogen and phosphorous fertilization, but with the latter this element of pod structure was slightly thicker

The influence of the applied nitrogen and phosphorous doses on the thickness of fibre layer is diverse for the tested bean varieties (Tab. 7). The thickness of this shell structure element of a bean pod of the Wawelska variety first decreased with the increase of the amount of sowed fertilizers reaching the minimal value at nitrogen dose of 30 kg·ha^{-1} and phosphorous dose of 80 kg·ha^{-1}, then increased reaching the maximum value with the largest doses of the used macroelements. A similar relation was observed for the Nida variety with nitrogen fertilization, where the difference in the thickness of fibre layer with the largest nitrogen dose was slightly lower than in that with zero dose. In the Wawelska variety with the increase of nitrogen dose a decrease of pod fibre layer thickness occurred, while in the Narew one firstly for the second nitrogen dose an increase of this pod element thickness and a decrease for the other doses were observed. The increase of nitrogen dose from 0 to 80 kg·ha^{-1} caused the increase of fibre layer thickness of the Nida and Warta pod shells, and for the dose of 120 kg·ha^{-1} this pod element was considerably thinner, similarly to the thickness with the zero phosphorous dose. In the Narew variety, the impact of phosphorous dose on the thickness of the relevant element of its pod structure was the most diverse. First a significant decrease in the relevant amount occured after the second dose, then an increase after the next dose and another decrease after the maximum phosphorous dose. Taking into account the mean values from the four bean varieties a slight falling tendency of pod fibre layer thickness with the increase of nitrogen dose can be observed.

Table 7. Thickness [μm] of the fibre layer of pods of the tested bean varieties for the applied doses of nitrogen and phosphorous

Fertilization	Dose [kg·ha^{-1}]	Narew	Nida	Warta	Wawelska	Average
Nitrogen	0	82,2 b	72,5 b	89,4 c	98,2	85,5 b
	30	83,8 b	58,6 b	73,6 b	88,5	76,1 ab
	60	79,1 ab	68,3 ab	71,8 b	95,8	78,8 ab
	90	65,4 a	69,5 ab	54,4 a	99,4	72,2 a
Phosphorous	0	104,4 b	63,7	69,3	106,1 ab	85,8
	40	80,5 a	71,2	69,7	98,4 ab	80,0
	80	96,9 ab	71,7	75,9	92,8 a	84,3
	120	87,2 ab	66,2	66,3	113,9 b	83,4

*different letters in column signify significant differences for the significance level α = 0.05

The pods of Wawelska variety were characterized by the fibre layer (Tab. 8) with the highest resistance to tearing and the largest deformation, whereas the highest module of elasticity was observed in the Warta pods. Fibre layer of Nida pods were characterized with the smallest value of the analyzed resistance parameters. The fibre layer of bean pods of Narew, Nida and Warta varieties was more resistant to tearing and underwent larger deformations with nitrogen fertilization. The modulus of elasticity reached higher values with nitrogen fertilization only for the Narew and Nida and lower ones for the Warta and Wawelska.

When analyzing mean values included in Table 9 and Figure 1 from four bean varieties of strength parameters of fibre layer it has to be emphasized that with the exception of deformation with nitrogen fertilization, these values significantly rise with the increase of sowed nitrogen and phosphorous. The used macroelements had the strongest

Table 8. Strength properties of fibre layer of pods of tested bean varieties

Specification	Narew	Nida	Warta	Wawelska	Average
Nitrogen fertilization					
Critical stress [MPa]	169,1 b	127,6 a	157,8 b	160,0 b	153,6
Deformation [%]	8,38 b	6,65 a	6,68 a	7,23 a	7,24
Modulus of elasticity [MPa]	1991,7 a	1932,2 a	2394,5 b	2216,4 ab	2133,7
Phosphorous fertilization					
Critical stress [MPa]	86,6 a	110,7 ab	132,3 b	180,6 c	127,6
Deformation [%]	4,18 a	5,60 b	6,01 b	9,17 c	6,24
Modulus of elasticity [MPa]	2089,3	1985,3	2199,4	1941,3	2053,8
Average of nitrogen and phosphorous fertilization					
Critical stress [MPa]	127,9 ab	119,2 a	145,0 b	170,3 c	140,6
Deformation [%]	6,28 a	6,13 a	6,35 a	8,20 b	6,74
Modulus of elasticity [MPa]	2040,5 a	1958,8 a	2296,9 b	2078,8 ab	2093,8

*different letters in row signify significant differences for the significance level α = 0.05

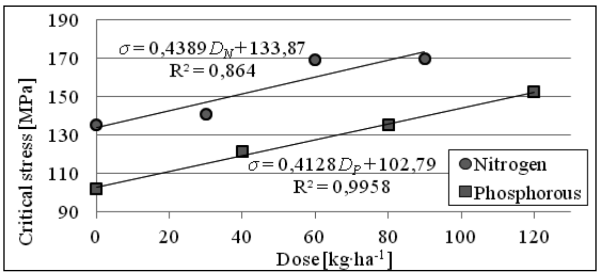
Table 9. Strength properties of fibre layer of pods of tested bean varieties for applied doses of nitrogen and phosphorous

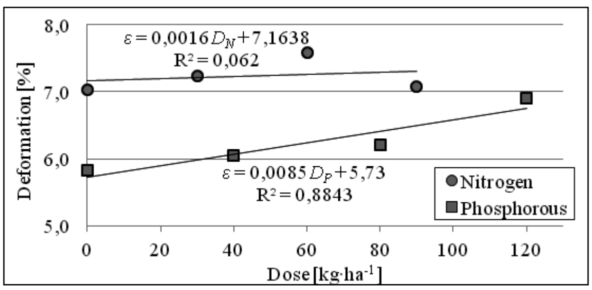
Specification	Dose [kg·ha^{-1}]	Narew	Nida	Warta	Wawelska
Nitrogen fertilization					
Critical stress [MPa]	0 30 60 90	158,7 a 162,1 ab 140,4 a 215,2 b	144,1 122,7 128,1 115,6	89,6 a 20,5 a 231,8 b 189,2 b	148,0 157,6 176,3 157,9
Deformation [%]	0 30 60 90	8,03 8,88 7,85 8,78	7,18 b 6,63 ab 7,05 ab 5,75 a	5,80 a 6,23 a 8,05 b 6,65 a	7,15 7,23 7,40 7,15
Modulus of elasticity [MPa]	0 30 60 90	1940,3 1795,2 1811,9 2419,4	1976,6 1845,6 1818,7 2087,8	1654,9 a 2037,2 a 2983,7 b 2902,2 b	2069,1 2266,0 2356,9 2173,7
Phosphorous fertilization					
Critical stress [MPa]	0 40 80 120	51,9 a 70,6 a 78,0 a 145,9 b	87,6 100,1 125,8 129,4	110,1 149,3 127,3 142,6	157,4 165,2 209,0 190,9
Deformation [%]	0 40 80 120	2,64 a 3,71 a 3,92 a 6,43 b	5,15 5,53 5,83 5,90	5,78 6,35 6,28 5,65	9,73 8,55 8,78 9,63
Modulus of elasticity [MPa]	0 40 80 120	1987,1 2045,6 2063,2 2261,2	1731,8 1785,2 2164,1 2260,3	1939,9 2394,2 1997,5 2465,8	1581,4 a 1882,2 ab 2339,8 b 1961,9 ab

*different letters in column signify significant differences for the significance level α = 0.05

impact on critical stress and the weakest one on modulus of elasticity. The applied doses of phosphorous had larger influence on the increase of stress and deformation than the doses of nitrogen, and the modulus slightly more increased with nitrogen fertilization.

Dependence of mean values of strength parameters of fiber layer bean pods on the doses of nitrogen and phosphorus are well described by a linear function (Fig. 1)





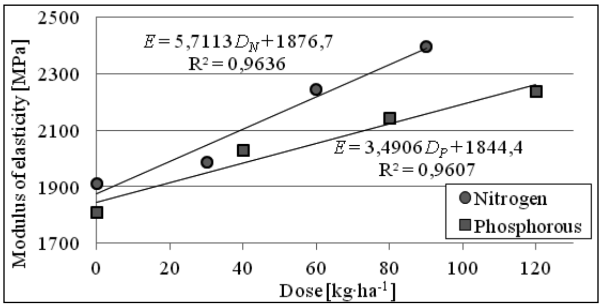


Fig. 1. Relation of mean values of strength parameters of fiber layer bean pods to the doses of nitrogen D_N and phosphorus D_P

CONCLUSIONS

1. Abdominal seam bundles of the tested bean varieties were characterized by larger width, thickness and cross section area as well as lower critical stress, deformation and modulus of elasticity than vascular bundles of dorsal seam.
2. In case of phosphorous fertilization abdominal and dorsal seam bundles of pods of the tested bean varieties were characterized with larger dimensions and deformation and lower strength to breaking and modulus of elasticity than with nitrogen fertilization. The exception constituted Narew variety in which, in

case of nitrogen fertilization, the dorsal seam was not lengthening as much and it was characterized with slightly larger modulus.

3. Abdominal seam bundles of Warta pods were the most resistant to breaking and underwent the largest lengthening, while these seams in the Wawelska variety beam pods were characterized with the highest modulus.
4. Fibre layer was thicker with phosphorous fertilization than with nitrogen fertilization, except for Warta variety pods.
5. The used macroelements had the strongest influence on critical stress and the weakest on modulus of elasticity of fibre layer in pod shell.
6. The applied phosphorous doses had a larger influence on the increase of stress and deformation than nitrogen doses, and modulus slightly more increased with nitrogen fertilization.

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WPŁYW NAWOŻENIA MINERALNEGO NA WŁAŚCIWOŚCI MECHANICZNE WYBRANYCH ELEMENTÓW BUDOWY WEWNĘTRZNEJ STRĄKÓW FASOLI

Streszczenie. Praca przedstawia charakterystykę właściwości mechanicznych wybranych elementów budowy strąków fasoli odmian Narew, Nida, Warta i Wawelska przy nawożeniu azotowym i fosforowym. Wiązki szwu brzusznego strąków fasoli charakteryzowały się mniejszym naprężeniem niszczącym, odkształceniem i modułem sprężystości od wiązek przewodzących szwu grzbietowego. Dla nawożenia fosforowego wiązki szwu brzusznego i grzbietowego strąków badanych odmian fasoli charakteryzowały się większym odkształceniem oraz mniejszą wytrzymałością na rozrywanie i modułem sprężystości niż przy nawożeniu azotowym. Zastosowane makroelementy najsilniej wpłynęły na naprężenie niszczące a najsłabiej na moduł sprężystości warstwy włókien w łupinie. Na wzrost naprężenia i odkształcenia miały większy wpływ zastosowane dawki fosforu niż azotu, zaś moduł nieznacznie bardziej zwiększył się przy nawożeniu azotowym.

Słowa kluczowe: strąk fasoli, elementy budowy, naprężenie niszczące, odkształcenie, moduł sprężystości.